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ORIGINAL ARTICLE

Crop Ecology, Management & Quality

Spinosad-based insecticide is an effective control method for the potato soil pests *Agriotes* sp. and *Melolontha* sp.

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Abstract

Potato (*Solanum tuberosum* L.) growers who would like to biologically control major soil pests of potato face an increasing challenge. Two pest species have a major impact on yield quality: white grubs (*Melolontha* sp.; Eschscholtz, 1829) and wireworms (*Agriotes* sp.; Fabricius, 1775). Farmers who want to grow potatoes in a sustainable fashion to reduce the quantity of chemical pesticides per hectare do not have many options. In this study, on-farm trials were conducted with a Spinosad-based granular insecticide in south-eastern Central Europe, Romania, in Brasov County, where *Melolontha* sp. and *Agriotes* sp. pests occur and cause severe damage to potato tubers. The insecticidal active substance Spinosad, belonging to the chemical family of spinosyns, is a naturally occurring mixture of two components, spinosyn A and spinosyn D, produced by the soil actinomycete *Saccharopolyspora spinosa*. In order to understand, optimize, and improve organic farming methods, a comprehensive study of Spinosad-based insecticides for controlling soil pests in potato was conducted across multiple locations and growing seasons. Spinosad treatment was consistently more effective than standard and untreated control groups in combating the two pests. The overall efficacy of Spinosad at 12 and 15 kg/ha resulted in 3.5% and 3.1% of tubers suffering damage, respectively, compared to the untreated control where 20.8% of tubers suffered damage (from both species). These results highlight the potential of Spinosad as an effective biocontrol method for potato pests in organic farming, contributing to sustainable agriculture practices and increased marketable yields.

Plain Language Summary

This 3-year study in Romania demonstrated that a granular Spinosad insecticide, a product derived from a naturally occurring soil bacterium, is a highly effective

Abbreviations: EU, European Union; GR, granular; HSD, honestly significant difference; IPM, integrated pest management; NTC, non-treated control; SC, suspension concentrate.

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and superior alternative for controlling the key potato (*Solanum tuberosum* L.) soil pests, wireworms (*Agriotes* sp.; Eschscholtz, 1829), and white grubs (*Melolontha* sp.; Fabricius, 1775). Spinosad treatments consistently reduced tuber damage from 20.8% in the untreated plots to approximately 3.1%–3.5%, showing a greater than 80% reduction in pest activity. Spinosad was significantly more effective than the conventional standard, Lambda-cyhalothrin, even at the same active ingredient rate, and ensured a higher marketable yield by reducing the severity of damage on affected tubers. The identified minimum effective dose of 12 kg/ha provides an economically viable and practical solution for small-scale farmers, while simultaneously supporting the European Green Deal's objective to reduce reliance on synthetic chemical pesticides.

1 | INTRODUCTION

The potato (*Solanum tuberosum* L.) ranks as one of the world's most important staple food crops, positioned alongside rice, wheat, and maize in terms of global production volume and contribution to food security (Soare, 2018). While the European Union (EU) remains a major global potato producer (Hajdu, 2020), Romania occupies a unique position characterized by a high volume of land dedicated to the crop, coupled with extreme farm fragmentation (Sterie et al., 2023). Historically holding the fourth largest potato cultivation area in the EU, Romania accounts for approximately 10% of the total EU potato area (Hajdu, 2020). However, the sector is dominated by small-scale holdings; Romania contains up to 41% of all EU agricultural holdings growing potatoes, with an average cultivation area of just 0.2 ha per farm (Sterie et al., 2023).

This fragmented structure is directly relevant to pest management, as it presents significant barriers to the adoption of advanced or capital-intensive technologies. Small-scale farmers often lack the specialized knowledge, resources, or equipment required for complex, multi-tactic integrated pest management (IPM) programs (Grasswitz, 2019). Consequently, there is a critical need for effective, accessible, and simple-to-implement solutions, such as single-application granular (GR) insecticides applied at planting, to protect marketable yields from soil-dwelling pests like *Agriotes* sp. (Eschscholtz, 1829) and *Melolontha* sp. (Fabricius, 1775) in these economically vulnerable systems.

While the recent contraction of the Romanian potato sector presents significant economic concerns (Sterie et al., 2023), it simultaneously provides a strategic and high-stakes environment for evaluating novel pest management interventions. Brasov County, and specifically the region of Tara Fagarsului, was selected for this study because it represents a “front line” of subterranean pest pressure, where the incidence of both *Agriotes* sp. and *Melolontha* sp. is historically

high and consistently leads to severe tuber damage. In such high-pressure zones, larval attacks can result in the loss of 40%–80% of the total harvested yield, making the region an ideal “worst-case scenario” testing ground for sustainable biocontrol methods (Kroschel et al., 2020).

The suitability of this location is further underscored by the presence of complex co-infestations. Unlike regions facing a single pest threat, the trial sites in Brasov County allow evaluation of the efficacy of a single-application GR formulation against a diverse and overlapping pest-complex under real-world agro-ecological conditions. This is relevant given the structural fragmentation of the Romanian potato sector. By conducting trials in this specific demographic and environmental context, this study demonstrates how a simple, at-planting biological solution can protect marketable yields and enhance farm-level profitability. The application and testing of an organic pesticide, such as Spinosad, in this environment acts as a case study for such challenging conditions while meeting the ambitious sustainability targets of the European Green Deal (Lorenzo et al., 2025).

The primary objective of this study was to evaluate the field efficacy of a Spinosad-based GR insecticide for the control of wireworms (*Agriotes* sp.) and white grubs (*Melolontha* sp.) in potato crops in Romania. The research was conducted through on-farm trials situated in Brasov County. Key evaluation parameters included the percentage of potato tubers exhibiting damage symptoms caused by the target pests relative to an untreated control. This research provides practical, evidence-based information on the potential of Spinosad as a sustainable tool to help Romanian potato growers manage critical soil pests within the current challenging agronomic and regulatory environment.

Wireworms (*Agriotes* sp.) are soil pests that hatch from clusters of up to 78 eggs deposited near the soil surface and inflict narrow tunnels and surface scarring on tubers (Kapsa, 2008). In contrast, larger white grubs (*Melolontha* sp.) originate from eggs laid 15- to 25-cm deep and excavate extensive

cavities (Chandel et al., 2013). Both pests migrate to the root zone to feed when soil temperatures reach 7°C–9°C. This physical damage severely devalues table and seed potatoes, necessitates expensive sorting, and often leads to downgrading or total lot rejection (Pelletier et al., 2013). Furthermore, feeding wounds serve as entry points for microbial pathogens that cause storage rot (Olsen et al., 2006). Because quality standards for potatoes are stringent, even minor pest populations result in significant economic losses for growers (Gabryś & Kordan, 2013; Pelletier et al., 2013; Vernon & van Herk, 2013; Weber, 2013).

Control of wireworms and white grubs presents considerable challenges due to several inherent biological and ecological factors. Their subterranean habitat makes populations difficult to monitor accurately and protects them from many surface-applied control measures. Both groups possess extended larval stages, spending multiple years (typically 2–5 years, depending on species and conditions) developing in the soil (Barsics et al., 2013). This multi-year residency means that an infestation established in one crop phase can persist and affect subsequent crops in the rotation, necessitating long-term management perspectives rather than single-season interventions. These pests are also polyphagous, feeding on the roots and underground parts of a wide range of crops and non-crop plants (Barsics et al., 2013). Wireworms, in particular, often thrive in grasslands or areas with abundant grass weeds, posing a heightened risk when such land is converted to arable cropping, including potatoes (Hermann et al., 2013). Their distribution within fields is often aggregated or patchy, further complicating the application of uniform control strategies (Poggi et al., 2021). There is also evidence suggesting that changing climatic conditions, such as warmer temperatures and increased frequency of drought periods, may be exacerbating the problem by creating conditions more favorable for wireworm development, survival, or feeding activity on moisture-seeking tubers (Kapsa, 2008).

Historically, the management of soil-dwelling pests like wireworms and white grubs in potato production relied heavily on the application of broad-spectrum, persistent synthetic insecticides. Organochlorines (e.g., lindane and aldrin), organophosphates, and carbamates were mainstays of control programs for decades. However, growing awareness and concern regarding the adverse environmental impacts of these chemicals, including their persistence in soil, detrimental effects on nontarget organisms, and potential risks to human health, have led to the progressive restriction and withdrawal of many of the most effective active substances from the market. The removal of these potent control agents, while environmentally necessary, may have contributed to an increase in the prevalence or visibility of damage caused by soil pests, as residual populations face less chemical pressure (Barsics et al., 2013). This challenge is even more acute for organic producers, who are prohibited from using synthetic pesticides (Razinger et al., 2020).

Core Ideas

- Granular Spinosad reduced potato tuber damage from soil pests (*Agriotes* sp. and *Melolontha* sp.) by over 80%.
- Spinosad provided superior control compared to the conventional synthetic standard, Lambda-cyhalothrin.
- The application rate of 12 kg/ha was identified as the minimum effective dose, aligning with sustainable agriculture and European Union Green Deal objectives.

Alternative management strategies, including cultural controls (e.g., crop rotation, tillage practices, and adjusting planting/harvest times; Barsics et al., 2013) and biological control approaches (e.g., using entomopathogenic fungi like *Metarhizium* spp. [Sorokin, 1879] or *Beauveria* spp. [Vuillemin, 1912] or employing trap crops; Nikoukar & Rashed, 2022), are being investigated and promoted. However, these methods often require a more sophisticated, integrated approach, demanding careful monitoring, precise timing, and adaptation to specific site conditions (Barsics et al., 2013). Their efficacy can be variable, particularly under high pest pressure, and may not always match the level of control previously achieved with broad-spectrum synthetic insecticides (Vernon et al., 2009).

The insecticidal active substance Spinosad, belonging to the chemical family of spinosyns, is a naturally occurring mixture of two components, spinosyn A and spinosyn D, produced by the soil actinomycete *Saccharopolyspora spinosa* (Mertz & Yao, 1990; Salgado, 1998). The biological origin of Spinosad makes it a candidate for integration into sustainable pest management systems, aligning with the objectives of reducing reliance on synthetic pesticides and promoting biologically based control strategies. Its profile allows for its use in certified organic production systems (subject to specific regulations) and as a component within broader IPM programs. The specific formulation evaluated in this research is a GR insecticide. This formulation is particularly relevant for targeting subterranean pests like wireworms and white grubs. Application of granules allows for the targeted delivery and incorporation of the active ingredient into the soil profile where the larvae reside and feed, offering advantages in terms of efficacy, persistence, and handling compared to foliar sprays or soil drenches for controlling these pests (Barsics et al., 2013).

While Spinosad is already recognized in potato IPM for its efficacy against surface pests such as the Colorado potato beetle (Bastarache et al., 2023), its application for subterranean pest control remains under-researched. This study

TABLE 1 Spinosad pesticide trial locations within Tara Fagarasului, Brasov County, Romania. Soils in this region are characterized primarily as cambisols and luvisols (Patriche et al., 2023).

Years	Trials	Location (GPS coordinates)	Planting date	Harvesting date	Location
First year: 2021	First trial	45.7925810, 24.7877600	May 25, 2021	September 20–22, 2021	Olteț
	Second trial	45.7323653, 24.7798448	May 25, 2021	September 21, 2021	Drăguș
	Third trial	45.7198512, 24.7853722	May 25, 2021	September 22, 2021	Drăguș
Second year: 2022	First trial	45.804446, 24.802409	May 4, 2022	August 30, 2022	Sâmbăta de Jos
	Second trial	45.790400, 24.804117	May 4, 2022	August 31, 2022	Sâmbăta de Jos
	Third trial	45.788050, 24.798783	May 4, 2022	September 1, 2022	Sâmbăta de Jos
Third year: 2023	First trial	45.774317, 24.779200	May 5, 2023	August 25, 2023	Drăguș
	Second trial	45.774950, 24.785383	May 5, 2023	August 26, 2023	Drăguș
	Third trial	45.732417, 24.779933	May 5, 2023	August 27, 2023	Drăguș
	Fourth trial	45.719767, 24.784183	May 5, 2023	August 27, 2023	Drăguș

addresses a critical gap by evaluating a specific GR formulation designed to overcome the limitations of liquid insecticides, which are prone to rapid degradation or fail to reach the soil target zone effectively (Fleurat-Lessard et al., 1998). Unlike suspension concentrates (SCs), the GR formulation utilized here provides a slow, persistent release of the active ingredient directly in the root zone where larvae reside. Furthermore, this research provides the first comprehensive field data on the dual-species efficacy of Spinosad against both wireworms (*Agriotes* sp.) and white grubs (*Melolontha* sp.). Field data regarding *Melolontha* is particularly scarce in existing scientific literature, which has traditionally focused on wireworm management. By utilizing a multi-year, 10-trial dataset from Romania, this study offers essential regional validation in a high-pressure environment where these co-infestations are common. This validation is vital for demonstrating that a simple, at-planting biological solution can meet the sustainability targets of the EU Green Deal while remaining practically accessible to small-scale growers who may lack the resources for complex, multi-tactic IPM programs.

2 | MATERIALS AND METHODS

2.1 | Trial site locations and description

On-farm trials were conducted using a Spinosad-based GR insecticide and were applied at planting of potatoes. From 2021 to 2023, 10 independent field trials were implemented: three trials in 2021, three trials in 2022, and four trials in 2023 (Table 1).

GR Spinosad was selected for application because of its slow release and persistence within the soil environment (Osgerby, 1972). Liquid Spinosad insecticide (SC formulation) usually breaks down due to its low vapor pressure

(Cleveland et al., 2002). The protection of the liquid insecticide then vanishes as the plant grows and develops. The new GR Spinosad formulation, composed of coated calcium carbonate granules, ensures longer protection to newly formed tubers (Li et al., 2021).

Insecticides were provided by SBM Company. Trials were conducted at sites in Tara Fagarasului, Brasov County, Romania (Figure 1), where pest incidences are known to be high. Spinosad was tested at different rates to study the efficacy against *Melolontha* sp. and *Agriotes* sp. local populations.

2.2 | Planting details

Commercial potato field productions were utilized with the variety Satina (Solana Group; biological category: Certified seed Class A) with a density of 53,333 tubers/ha. Spacing was 75 cm inter-row width, with a distance between tubers/row of 25 cm. The planting depth was 10 cm.

Regarding fertilization before planting, 1 t/ha of fertilizer was broadcast for each trial as per standard local practice (Manna Biorit NPK Organic, Hauert HBG Dünger; chemical composition: 4% N, 3% P₂O₅, 8% K₂O, 1.0% MgO, 2.4% S, and 7.4% CaO). For soil pH amendment, 1 t/ha of lime was applied using the same method (Dolomite, Cemrom S.A.; chemical composition: 53%–59% CaCO₃ and 36%–42% MgCO₃). A chisel plow was used for incorporation in the soil and for seedbed preparation at each trial location.

Five pesticide treatments were tested as follows: non-treated control (NTC); a GR insecticide based on Spinosad, applied in three rates (9, 12, and 15 kg/ha); and a GR insecticide based on Lambda-cyhalothrin with the recommended dose of 15 kg/ha. The GR insecticides were applied directly in the row during planting and applied using custom-designed application machinery manufactured by France Agri, provided by AgroProspect (Figure S1).

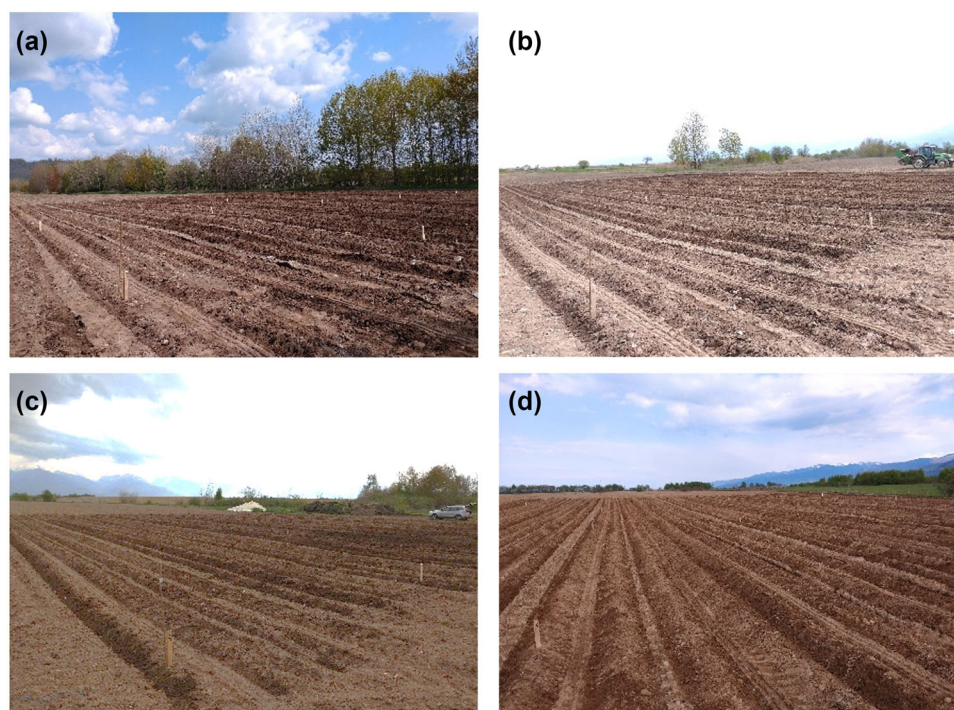


FIGURE 1 Spinosad-potato trial site locations in Sâmbăta de Jos (a–c) and Drăguș (d), Tara Fagarasului, Brasov County, Romania.

TABLE 2 Treatments and application rates of Spinosad insecticide to 10 potato field trials across 3 years (2021–2023).

Treatment No.	Description	Formula concentration (g/kg)	Form type	Rate (kg/ha)	Alternate rate (g ai/ha)
1	Untreated control	n/a	n/a	0	0
2	Spinosad	4	GR	9	36
3	Spinosad	4	GR	12	48
4	Spinosad	4	GR	15	60
5	Lambda-cyhalothrin	4	GR	15	60

Abbreviation: GR, granular; n/a, not applicable.

2.3 | Experimental design

Each trial site contained five treatments with a control check included and four replicates in randomized blocks. Plots were 60 m² in size. The levels of treatment used at each site over the three trial years are shown in Table 2.

2.4 | Harvest and grading

Final assessments of tubers were made at harvest (118–120 days, 2021; 118–120 days, 2022; 112–114 days, 2023, after planting), according to the EPPO guidelines (EPPO, 2005a; EPPO, 2004; EPPO, 2012). During harvest, the numbers of healthy and infested tubers were determined, taking 120 (minimum amount is 100 according to the EPPO guidelines) tubers of marketable size (4–8 cm in diameter) from each of the plots, from a minimum of 10 random spots within each plot.

See Figure 2, for example, for photographs of *Melolontha* sp. and *Agriotes* sp. damage to tubers. Such damage severely impacts the marketable yield of potato crops in organic systems. The number of holes on each tuber was counted, including scars that plants had healed. The percentage of tubers damaged and the mean number of holes per tuber were counted and calculated. Tubers of unmarketable size (<3.9 cm or >8.1 cm in diameter) were not included in the total yield calculations or in the pest damage assessments.

2.5 | Wireworm larval density measurements

Wireworm larval density was measured in the 2023 field trials only. Six baited traps were positioned in a “W” pattern within each field trial location on May 5, as per EPPO guidelines (EPPO, 2005a). The first data collection commenced on May 10 and continued every 10 days until August 25.



FIGURE 2 Examples of damage to potato tubers as a result of *Melolontha* sp. (a) and *Agriotes* sp. (b) grub infestations. The large cavity in (a) as a result of grubs feeding on the tuber. In (b), an *Agriotes* sp. larva can be seen protruding from a hole burrowed into the tuber.

Due to supply chain issues in 2021 and 2022 as a result of the Covid-19 pandemic, it was not possible to conduct larval density assessments for wireworms in those years. Larval monitoring of white grubs is not part of the EPPO guideline method (EPPO, 2004) and was not conducted. This is in part due to the depth at which the pests reside in the soil (10- to 15-cm deep) and the hard, rocky nature of the local soil.

2.6 | Statistical analysis—Yield (total, marketable, and unmarketable)

Statistical computations were performed using Python (v3.x), utilizing the statsmodels library for parametric modeling (analysis of variance [ANOVA], Tukey's honestly significant difference [HSD]). Given the structural design of the experiment, "Trial number" was treated as a nested variable within each "Year."

To evaluate the efficacy of the insecticidal interventions while accounting for environmental and experimental variability, the statistical approach categorized variables into fixed and random components. Pesticide treatment served as the primary fixed effect, comprising five levels: an NTC, three discrete application rates of GR Spinosad (9, 12, and 15 kg/ha), and the conventional synthetic standard of LRambda-cyhalothrin (15 kg/ha). To address the broad range of uncontrolled conditions inherent in the on-farm trials, year (2021–2023) and trial sites (10 independent locations) were incorporated as random factors. This structure allowed the analysis to account for temporal fluctuations in weather patterns and spatial variations in soil properties across the study

region. Furthermore, the randomized block design utilized at each site treated individual replicates as random factors to control for localized field heterogeneity, ensuring that the observed differences in marketable yield and pest damage were primarily attributable to the fixed treatment effects.

The yield data from the 10 independent field trials conducted between 2021 and 2023 were pooled for collective analysis to provide a robust and generalizable assessment of GR Spinosad's efficacy. Although individual years and trial sites introduced uncontrolled variability (specifically differing weather conditions and heterogeneous soil properties), these were treated as independent factors within the broader experimental framework. The primary objective was to identify a consistent pattern of pest control that transcends localized environmental "noise," ensuring the findings are representative of the diverse agro-ecological landscape of Brasov County.

To evaluate the impact of the insecticidal treatments on the quality of the potato yield, the count data for marketable and unmarketable tubers were converted into yield proportions. For each of the three trial years (2021–2023), the proportion of unmarketable tubers was calculated by dividing the number of unmarketable tubers by the total tuber count (marketable + unmarketable) within each treatment group. Because proportional data frequently violate the standard linear model assumptions of normality and homoscedasticity, the calculated proportions were subjected to an arcsine square-root transformation ($\arcsin(\sqrt{p})$) prior to statistical testing. This transformation stabilizes the variance and normalizes the distribution of binomial proportion data. A one-way analysis of variance (ANOVA) was performed on the transformed data to test for global, statistically significant differences in the proportion of unmarketable tubers among the five treatment groups. Following a significant ANOVA ($p \leq 0.05$) result, post hoc pairwise comparisons were conducted using Tukey's HSD test to identify specific differences between individual treatments while controlling the family-wise error rate at $\alpha = 0.05$.

While a mixed-effects modeling framework, such as linear mixed models for yield and generalized linear mixed models for pest counts, is a powerful tool for hierarchical and nested experimental designs, a fixed-effects ANOVA and nonparametric approach was selected for this study to prioritize statistical robustness, transparency, and strict adherence to distributional constraints. The justification for this approach is based on three primary methodological considerations: (1) the limited number of temporal levels for variance partitioning, (2) distributional robustness for non-normal count data, and (3) model complexity and interpretability. The chosen general linear model approach and robust parametric tests provide a conservative, assumption-light, and mathematically stable assessment of the treatment effects compared to a mixed-effects framework.

2.7 | Statistical analysis—Spinosad dose–response

To visually evaluate the dose-dependent efficacy of the Spinosad treatments, a preliminary empirical dose–response analysis was conducted. Yield data corresponding to the Spinosad treatments were extracted for analysis, with the untreated control serving as the 0 kg/ha baseline. The Lambda-cyhalothrin treatment was excluded from this specific analysis, as it was only tested at a single concentration, precluding the evaluation of a dosage gradient. To identify generalized, multi-year trends and reduce season-to-season noise, the dependent variables (marketable yield and unmarketable yield, measured in t/ha) were averaged across the three experimental years (2021, 2022, and 2023) for each of the four Spinosad dosage levels. This aggregation generated a single mean response value per dose. Scatter plots were then constructed mapping the Spinosad dose (independent variable) against the mean yield responses (dependent variable). To illustrate the empirical trajectory of the dose–response relationship (specifically to identify points of rapid response and points of diminishing returns [asymptotes]), the mean data points were connected via linear interpolation. All data aggregation and visual rendering were performed using the pandas and matplotlib.pyplot libraries in Python (v3.x).

2.8 | Statistical analysis—Wireworm larval density

To statistically evaluate changes in wireworm density over the trapping season in 2023, a longitudinal analysis was conducted. The experimental design was treated as repeated measures, as counts were recorded from the same four spatially distinct field trials across eleven sequential trapping dates. Prior to testing, the temporal count data were assessed for normality using the Shapiro–Wilk test. The dataset exhibited a severe departure from a normal distribution ($p \leq 0.001$), characterized by zero-inflation and overdispersion, driven by highly localized spatial patchiness. Consequently, parametric repeated-measures modeling (e.g., repeated measures-ANOVA) was deemed inappropriate.

To appropriately handle the non-normal, repeated-measures data structure, a nonparametric Friedman chi-square test was utilized. This rank-based test was employed to determine if there were statistically significant global differences in wireworm densities across the eleven sampling dates, treating the four individual field trials as the blocking subjects to account for inter-trial spatial variability. All temporal statistical evaluations and distributional assumption checks were executed using Python (v3.x), utilizing the scipy.stats library.

2.9 | Statistical analysis—Pest damage severity

To determine if there were global, statistically significant differences in damage severity across the main experimental factors (Year and Treatment), a Kruskal–Wallis H -test was utilized. Where the Kruskal–Wallis test indicated a significant global effect ($p \leq 0.05$), post hoc pairwise comparisons were conducted using the Mann–Whitney U test to identify specific differences between group medians (e.g., comparing each insecticidal treatment against the untreated control).

To statistically evaluate the severity of tuber damage caused by *Agriotes* sp. and *Melolontha* sp., the frequency distribution of feeding holes per damaged tuber was analyzed. Damage was recorded categorically (ranging from “1 hole” to a right-censored category of “7+ holes”), and the contingency tables were first unpacked into a continuous, long-format dataset representing individual damaged tubers to facilitate distributional analysis. An initial assessment of the data distributions was conducted using the Shapiro–Wilk test. The distributions of hole counts for both *Agriotes* sp. and *Melolontha* sp. violated the assumption of normality ($p \leq 0.001$), which is characteristic of zero-truncated, overdispersed, and right-censored ecological count data. Consequently, a non-parametric analytical pipeline was employed. To strictly control the family-wise error rate and mitigate the risk of Type I errors (false positives) associated with multiple pairwise comparisons, a Bonferroni correction was applied to the significance threshold. For the severity of tuber damage (number of holes per tuber), the significance threshold was defined at an adjusted α level of 0.005.

These procedures and data transformations were performed using Python (v3.x), utilizing the scipy.stats library for nonparametric hypothesis testing and the pandas library for data reconstruction. Visualizations were generated using matplotlib and seaborn.

3 | RESULTS

3.1 | Marketable versus unmarketable yields

The study was conducted over 3 years, in a randomized manner, so the year, trial, and replicates act as independent factors that might influence the homogeneity of data. Weather conditions differed year-to-year, as well as the soil properties on different parcels. Despite these uncontrolled factors, a significant effect was seen concerning the different treatments applied, specifically, for the amounts of unmarketable yields. All tested dosages of Spinosad significantly reduced the proportion of unmarketable tubers compared to the untreated control, whereas the standard Lambda-

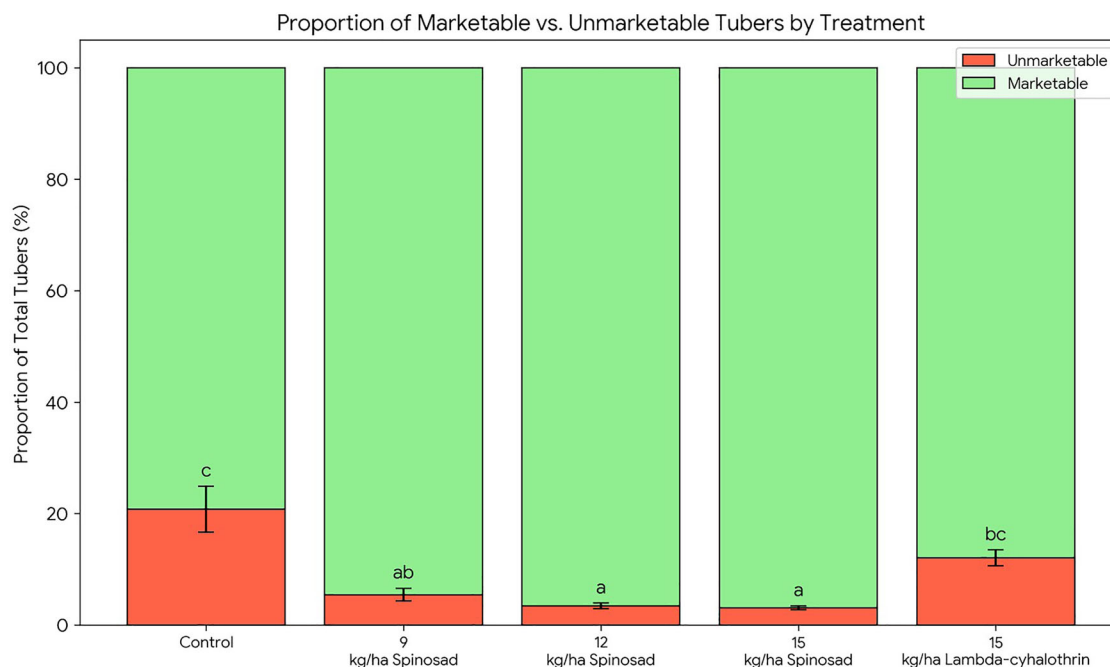


FIGURE 3 Effect of insecticidal treatments on the proportional yield of marketable and unmarketable tubers. The 100% stacked bar chart illustrates the mean percentage of unmarketable (bottom segment) and marketable (top segment) potato tubers relative to total potato tuber yield. Data represent the multi-year average across three consecutive field seasons (2021–2023). Error bars applied to the unmarketable segments denote the standard error of the proportion across the three trial years. Different lowercase letters above the bars indicate statistically significant differences in the proportion of unmarketable tubers among treatments ($p \leq 0.05$), as determined by a one-way analysis of variance (ANOVA) and post hoc Tukey's honestly significant difference (HSD) test performed on arcsine square-root transformed data.

cyhalothrin application did not achieve statistical significance (Figure 3).

The proportion of unmarketable tubers relative to the total harvested yield across all years and trials was evaluated to determine the impact of the treatments on crop quality. A one-way ANOVA performed on the arcsine square-root transformed proportions revealed a highly significant global effect of the insecticidal treatments on the unmarketable tuber fraction ($F_{4,10} = 19.00$; $p = 0.0001$). Post hoc pairwise comparisons using Tukey's HSD test demonstrated that applications of Spinosad were highly effective at preserving tuber quality. All tested dosages of Spinosad significantly reduced the proportion of unmarketable tubers compared to the untreated control. Specifically, applications at 9 kg/ha ($p = 0.001$), 12 kg/ha ($p = 0.0003$), and 15 kg/ha ($p = 0.0002$) successfully suppressed damage, dropping the unmarketable multi-year average from approximately 20.8% in the control plots to between 3.1% and 5.4% in the Spinosad-treated plots. Notably, there were no statistically significant differences in the proportion of unmarketable tubers among the three Spinosad dosages ($p \leq 0.64$ for all pairwise comparisons).

In contrast, Lambda-cyhalothrin (15 kg/ha) provided no significant protection of tuber quality. The proportion of unmarketable tubers in plots treated with Lambda-cyhalothrin (~12.0%) was not statistically distinguishable

from the untreated control ($p = 0.099$). Furthermore, the standard Lambda-cyhalothrin treatment was significantly outperformed by the higher dosages of Spinosad, yielding a significantly higher proportion of unmarketable tubers than both the 12 kg/ha ($p = 0.014$) and 15 kg/ha ($p = 0.01$) Spinosad applications. The Lambda-cyhalothrin treatment had the same dose of active ingredient/ha (60 g ai/ha) as the highest Spinosad application (Table 2), but was much less effective at reducing unmarketable yields.

3.2 | Spinosad dose response

The empirical dose–response curves presented in Figure 4 demonstrated a nonlinear relationship between Spinosad application rates and crop yield, characterized by a rapid initial response followed by a plateau of diminishing returns. For unmarketable yield (driven by pest damage), the steepest decline occurred between the untreated control (0 kg/ha) and the lowest tested dosage of 9 kg/ha, dropping from a multi-year average of roughly 5.5–1.46 t/ha. Increasing the Spinosad dosage further to 12 and 15 kg/ha provided minimal additional reductions in unmarketable yield, establishing a lower asymptote at approximately 0.8–0.9 t/ha. An inverse, growth-to-plateau trend was observed for marketable yield.

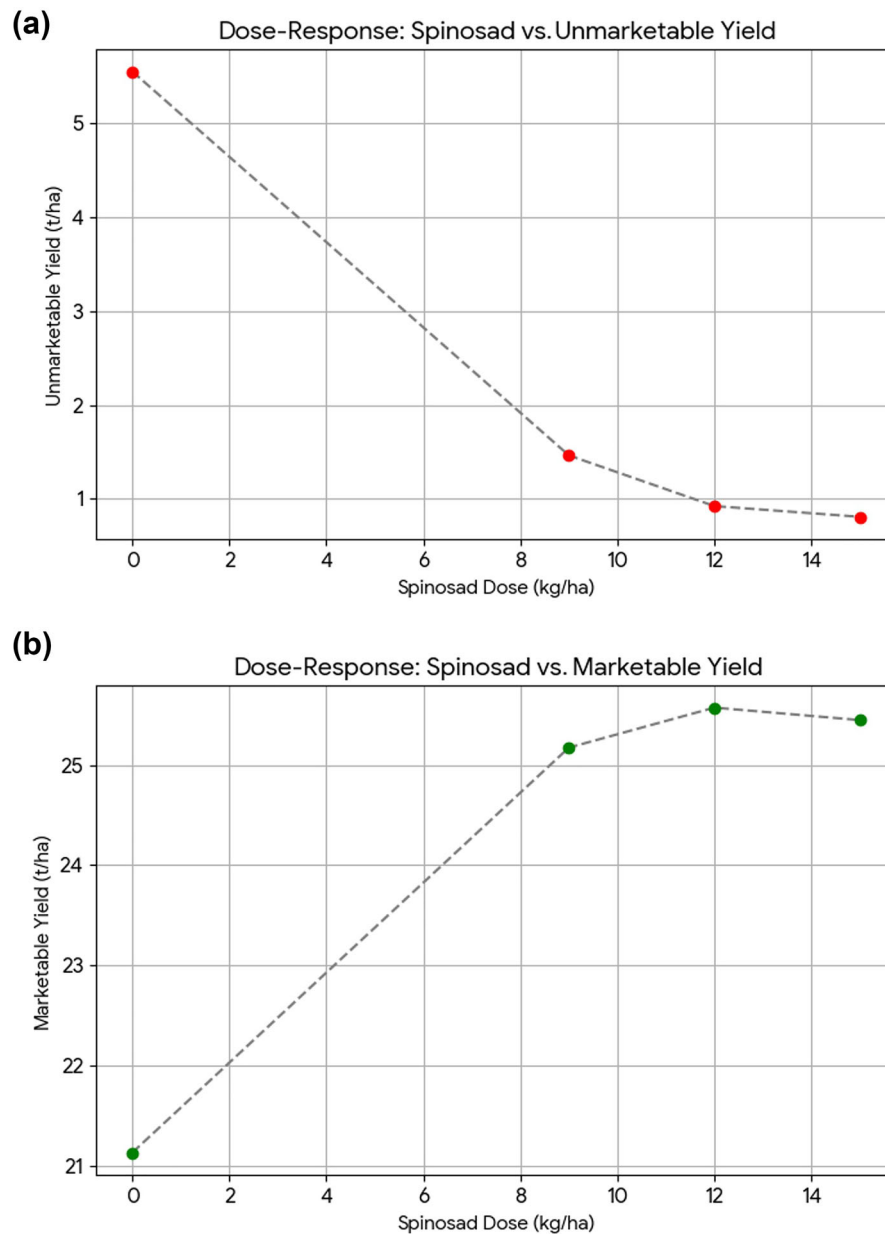


FIGURE 4 Dose–response relationship between Spinosad application rate and crop yield. The panels illustrate the multi-year mean unmarketable yield (a) and marketable yield (b) measured in tonnes per hectare (t/ha). Data points represent the average yields across three consecutive trial years (2021–2023) at Spinosad application rates of 0 (untreated control), 9, 12, and 15 kg/ha. Dashed lines denote the empirical trajectory between the observed means, highlighting a rapid initial response followed by diminishing returns (plateau) at doses exceeding 9–12 kg/ha. The 15 kg/ha Lambda-cyhalothrin treatment was excluded from this visualization as it was evaluated at only a single concentration, precluding continuous dose–response curve generation.

The initial application of 9 kg/ha yielded a substantial increase in marketable crop (averaging 25.1 t/ha compared to the 21.1 t/ha control). However, subsequent dosage increases to 12 and 15 kg/ha produced negligible further gains, with marketable yields plateauing at 25.5 t/ha. Collectively, these dose-response trends indicate that while Spinosad is highly effective at reducing pest damage and improving marketable yield, applications exceeding 9–12 kg/ha offer no substantial agronomic benefit.

3.3 | Wireworm larval density

Despite an initially high average across the four field trials, no significant differences were detected in wireworm density per hectare over time in the 2023 field trial ($p = 0.686$; Figure 5). The lack of statistical significance is due to extreme spatial variability (patchiness) between the four field trials, indicating that each location had their own distinct levels of infestation, despite relatively close proximity within Brasov County

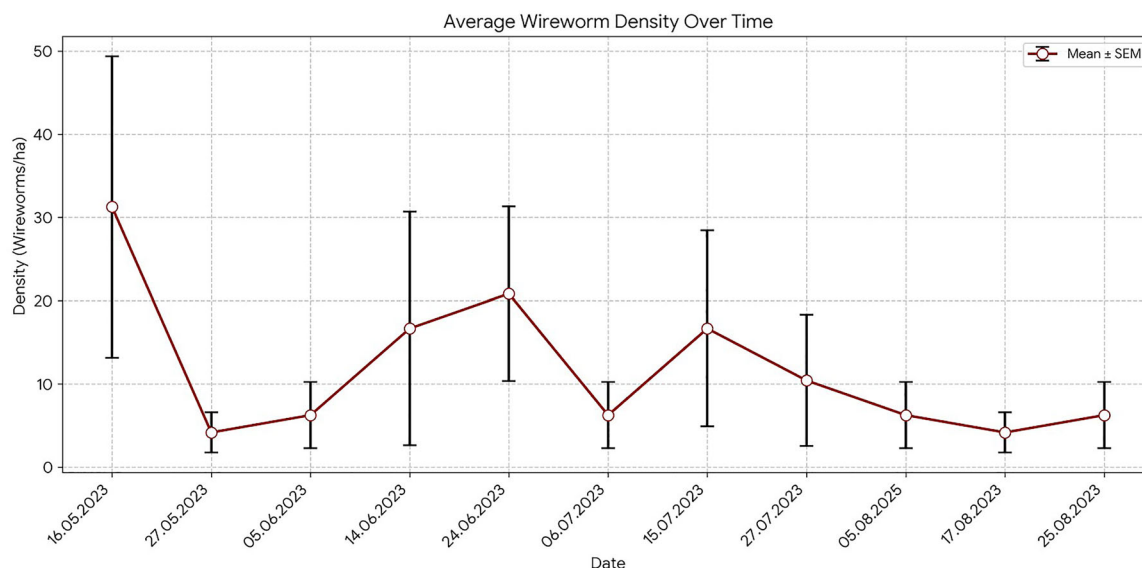


FIGURE 5 Temporal dynamics of wireworm density across the 2023 field season. The line chart illustrates the average density of wireworms (*Agriotes* sp.), extrapolated to individuals per hectare, across 11 sequential trapping dates from mid-May to late August. Data points represent the mean density calculated across four independent field trials (each covering 1200 m² with six traps). Error bars denote the standard error of the mean (SEM), highlighting the degree of spatial variability between the four trial locations on each respective sampling date.

(Table 1). Because the spike in density on May 16 only happened in trial 1, and the mid-June spike only happened in trial 3, it can be concluded that these changes are driven by highly localized spatial factors rather than a uniform, time-driven temporal trend.

3.4 | Pest damage to tubers

On average, 96.5% of total tubers treated with Spinosad treatment 12 kg/ha were undamaged by either *Agriotes* sp. and/or *Melolontha* sp. (Figure 6). The Spinosad treatment at a concentration of 15 kg/ha was slightly more effective than the total average, with 96.8% of tubers undamaged across the 3 years of trials. Since overall the control group had 78.6% of tubers undamaged (on average) and the alternative group had 87.7% (on average), the effectiveness of the Spinosad treatment at 12 kg/ha was robust (83.5% undamaged tubers). The Spinosad concentration of 15 kg/ha was more effective overall, reducing pest damage by 85.2% relative to the control ($p \leq 0.001$). Compared to the standard Lambda-cyhalothrin 15 kg/ha, overall effectiveness of 12 kg/ha Spinosad treatment (measured as the percentage reduction of affected tubers) was 73%.

When looking at the effects of the different pest species separately (Figure 7), overall effectiveness of 12 kg/ha Spinosad treatment in controlling *Agriotes* sp. activity was 83.3%, while for *Melolontha* sp., the reduction was 87.4% (versus the control). Compared to the alternative treatment, 15 kg/ha Lambda-cyhalothrin, the effectiveness of 12 kg/ha Spinosad

treatment in controlling the *Agriotes* sp. activity was 69.8%, while for *Melolontha* sp., it was up to 81% on average.

Not only was the percentage of unaffected tubers increased when applying the Spinosad treatments, but the amount of damage on the individual tubers dropped significantly (Figure 8). Nonparametric global evaluations indicated that damage severity was significantly influenced by both the trial year and the applied insecticidal treatments for both *Agriotes* sp. ($\alpha \leq 0.001$) and *Melolontha* sp. ($\alpha = 0.002$). However, post hoc pairwise comparisons revealed distinct treatment dynamics between the two pest species. Treatment interventions were highly effective at mitigating *Agriotes* sp. damage. All tested application rates of Spinosad (9, 12, and 15 kg/ha) significantly reduced the frequency of feeding holes per tuber compared to the untreated control ($\alpha \leq 0.005$). In contrast, Lambda-cyhalothrin (15 kg/ha) failed to significantly suppress damage severity relative to the untreated control. Furthermore, Spinosad applied at both 9 and 12 kg/ha proved statistically superior to Lambda-cyhalothrin, yielding significantly fewer holes per tuber.

The impact of the experimental treatments on *Melolontha* sp. was less pronounced. After applying conservative statistical corrections for multiple comparisons, neither the baseline 9 kg/ha Spinosad treatment nor the 15 kg/ha Lambda-cyhalothrin treatment provided a statistically significant reduction in feeding holes compared to the untreated control. The only significant differentiation observed among the treatments was between the 9 and 12 kg/ha Spinosad applications ($\alpha = < 0.001$), with the 12 kg/ha dose resulting in significantly less severe pest damage. This suggests

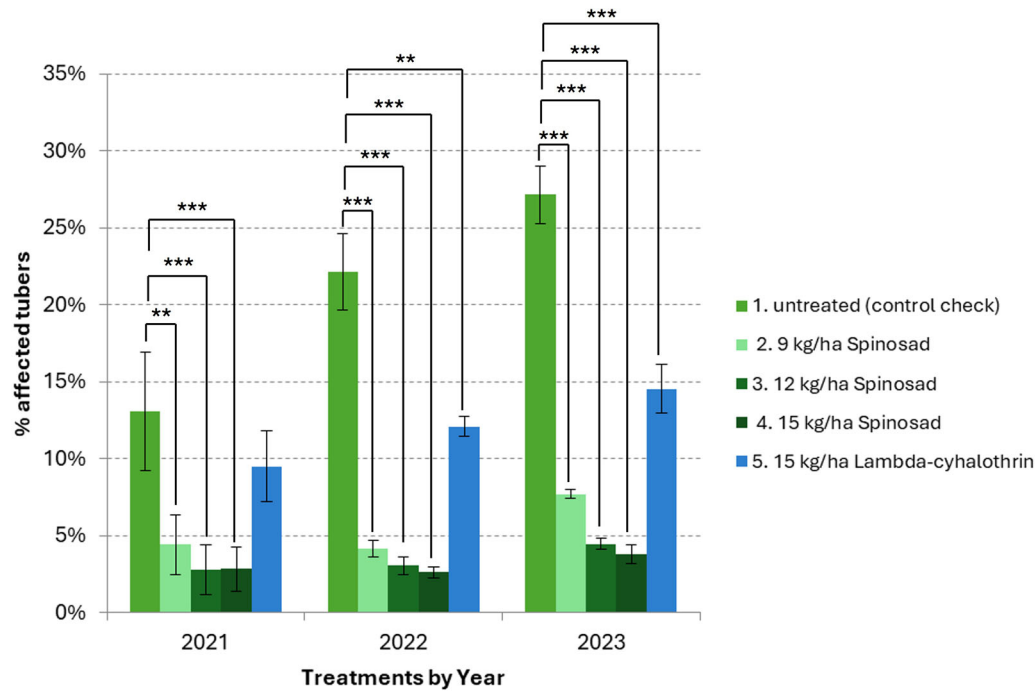


FIGURE 6 The percentage of tubers affected by *Melolontha* sp. and *Agriotes* sp. pest damage per experimental year and pesticide treatment. Error bars represent standard error of the mean. Asterisks denote statistical significance (Kruskal–Wallis H -tests and Mann–Whitney U tests with Bonferroni correction) between treatments relative to the untreated control: ** $p \leq 0.01$ and *** $p \leq 0.001$.

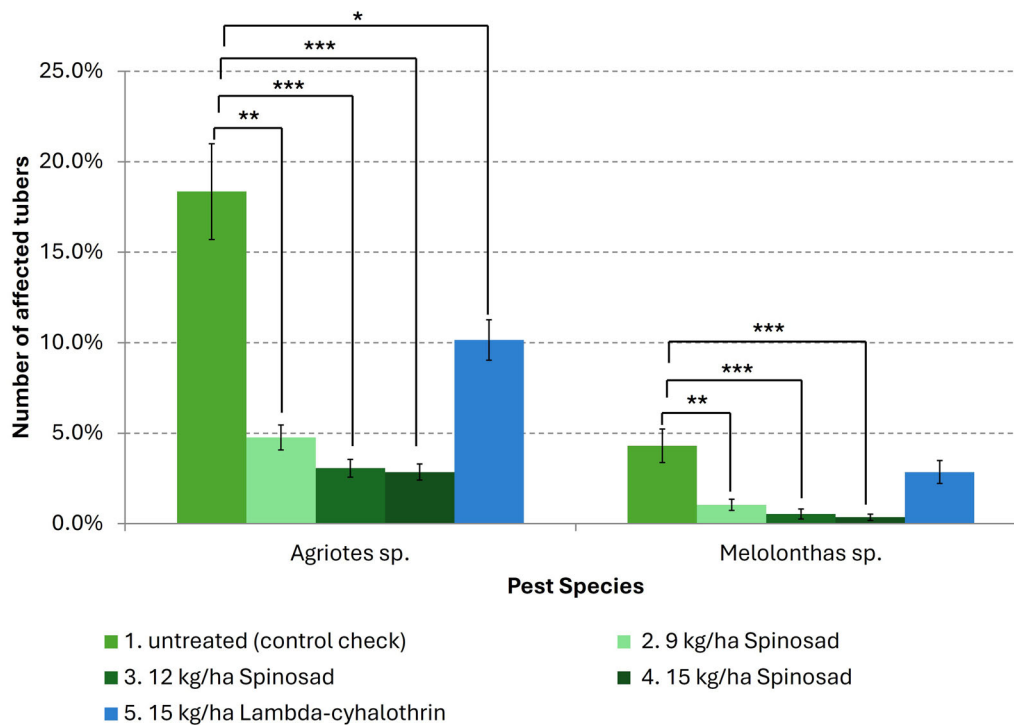


FIGURE 7 Average percentage of affected tubers according to pest species across 3 years of field trials ($n = 10$ trials, total). Error bars represent standard error of the mean. Asterisks denote statistical significance (Kruskal–Wallis tests and Mann–Whitney U tests with Bonferroni correction) between treatments relative to the untreated control: * $p \leq 0.05$, ** $p \leq 0.01$, and *** $p \leq 0.001$.

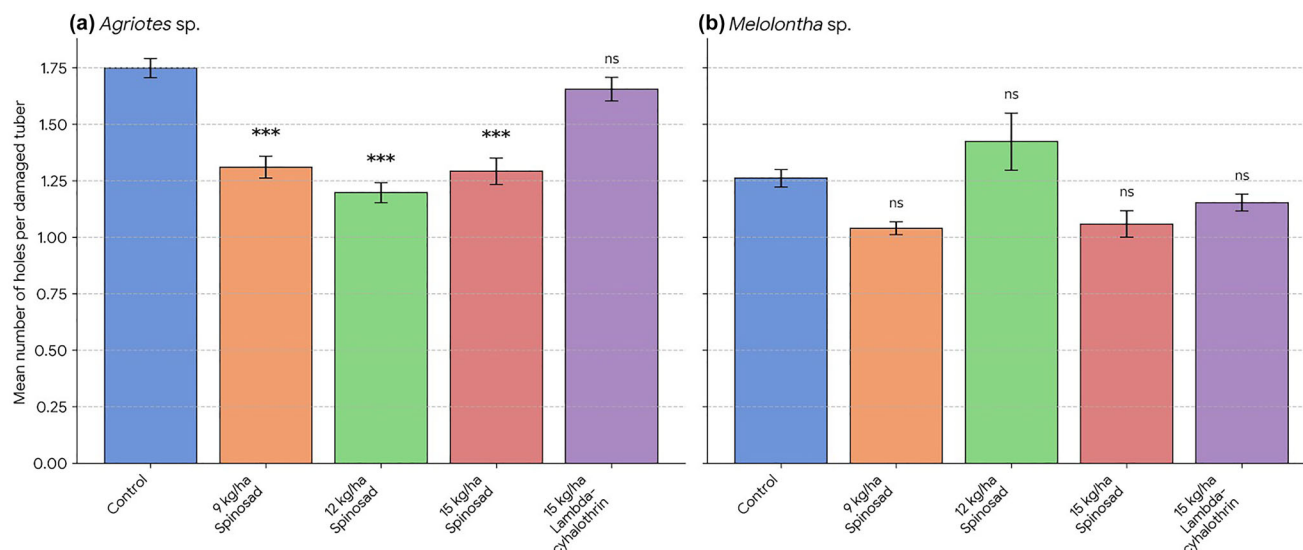


FIGURE 8 Effect of insecticidal treatments on the severity of tuber damage caused by *Agriotes* sp. and *Melolontha* sp. The bar charts display the mean number of feeding holes per damaged tuber across the 3-year trial period (2021–2023) for (a) *Agriotes* sp. and (b) *Melolontha* sp. Error bars represent the standard error of the mean. Because the underlying count data violated the assumption of normality, statistical assessments were performed using the nonparametric Kruskal–Wallis test followed by post hoc Mann–Whitney U pairwise comparisons against the untreated control. To account for multiple comparisons, a conservative Bonferroni-adjusted alpha threshold ($\alpha = 0.005$) was utilized for significance. Asterisks indicate a statistically significant reduction in damage severity compared to the untreated control ($*\alpha \leq 0.005$; $**\alpha \leq 0.001$; $***\alpha \leq 0.0001$), whereas “ns” denotes no significant difference.

that a higher dosage threshold may be required to achieve measurable efficacy against *Melolontha* sp. compared to *Agriotes* sp. Overall, there was no significant difference between the 12 and 15 kg/ha Spinosad treatments for either *Agriotes* sp. ($\alpha = 0.37$) or *Melolontha* sp. ($\alpha = 0.03$). This suggests that using doses higher than 12 kg/ha would see diminishing returns for the grower.

4 | DISCUSSION

4.1 | Efficacy of the granular Spinosad formulation

The findings suggest that the Spinosad-based GR insecticide provides effective control against mixed populations of *Agriotes* sp. and *Melolontha* sp. Specifically, treating plots with 12–15 kg/ha reduced tuber damage from 20.8% in untreated controls to 3.1%–3.5%. This represents a reduction in pest damage of over 80%, which may translate to higher marketable yields for growers. Notably, the 87.4% reduction in damage attributable to *Melolontha* sp. relative to the control addresses a significant gap in applied pest management literature, as field data for Spinosad’s performance against this genus has been historically scarce (Barsics et al., 2013). These observations may be linked to the GR formulation, which utilizes coated calcium carbonate granules designed for

slow, persistent release within the soil profile (Li et al., 2021). This targeted delivery likely helps maintain protective concentrations in the root zone during critical tuber development periods when they are most vulnerable to subterranean larvae.

The application of GR Spinosad product relies on in-furrow delivery during the potato planting phase. In the experimental trials, we utilized specialized application machinery (Figure S1), which was designed to deliver the granules directly into the planting row for small experimental plots. However, a key point is that this method is inherently compatible with standard agricultural machinery typically used for commercial potato production. By integrating the insecticide application into the planting process, growers can avoid the need for capital-intensive foliar spray equipment or the complex operational logistics associated with liquid soil drenches. This in-furrow approach ensures that the coated calcium carbonate granules are incorporated precisely into the root zone. This placement is critical because it protects the active ingredient from the photodegradation and microbial action that often compromise the efficacy of liquid formulations applied to the soil surface (Cleveland et al., 2002). Ultimately, the simplicity of this single-pass application provides a more accessible pathway for small-scale farmers to manage critical soil pests. It effectively removes the barriers to adoption by eliminating the requirement for specialized technical knowledge, frequent field scouting, or multiple passes through the field with heavy machinery.

4.2 | Comparative performance and optimal dosing

In these trials, the GR Spinosad formulation was more effective than the conventional synthetic standard, Lambda-cyhalothrin, even when applied at an identical active ingredient rate of 60 g ai/ha. While the synthetic pyrethroid reduced overall tuber damage by 42.6%, Spinosad achieved reductions exceeding 80%. This disparity may stem from Spinosad's ability to bind to soil particles, potentially extending its half-life up to 200 days when protected from light (Cleveland et al., 2002).

The data support a minimum effective dose of 12 kg/ha (48 g ai/ha), as no statistically significant difference in efficacy was observed between the 12 and 15 kg/ha treatments for *Agriotes* sp. or *Melolontha* sp. Beyond reducing the incidence of attack, Spinosad appeared to mitigate the severity of damage; 81% of damaged tubers in Spinosad-treated plots exhibited only a single hole, compared to higher frequencies of multiple punctures in control and Lambda-cyhalothrin groups. This suggests a sublethal effect where larvae may cease feeding rapidly upon contact with the treated zone.

4.3 | Sector-level and policy implications

For the Romanian potato sector, characterized by extreme farm fragmentation, a single-application in-furrow GR product may represent an accessible technology. Such formulations lower the barriers to adoption by reducing the need for capital-intensive equipment or complex scouting required by multi-tactic IPM programs.

These results align with the EU's Farm to Fork strategy, which targets a 50% reduction in chemical pesticide use by 2030 (Manshanden et al., 2023). The transition from a synthetic pyrethroid to a biologically derived alternative like Spinosad did not result in a yield penalty or compromised crop protection in this context. However, to mitigate the risk of field-evolved resistance (already documented in pests like the Colorado potato beetle; Schnaars-Uvino & Baker, 2021) Spinosad should be used as part of a diversified strategy including crop rotation.

4.4 | Limitations and future research

While this study provides robust data collected from ten trial sites over a 3-year period, acknowledging its inherent limitations is essential for guiding future investigations. Because the research was situated exclusively within the agroecological context of Brasov County, Romania, the direct generalizability of these findings to other regions requires further confirmation. Future trials should evaluate the efficacy of the

GR Spinosad formulation across diverse soil types (particularly those with varying organic matter content and pH levels) as well as different climatic conditions and pest population genetics.

Regarding environmental sustainability, Spinosad is generally considered to have a favorable profile with low toxicity to many nontarget organisms (Santos et al., 2019). However, the long-term, multi-season impact of repeated annual GR applications on the broader soil ecosystem remains to be fully characterized. It is therefore imperative that future research studies assess the effects on soil mesofauna, beneficial arthropods, and microbial communities to ensure the long-term ecological stability of the potato agroecosystem.

Furthermore, a comprehensive cost-benefit analysis is necessary to quantify the specific economic advantages for Romanian smallholders. Such an analysis should model the input costs of the Spinosad product against the net value of protected marketable yields, while factoring in volatile potato prices and the potential for reduced national reliance on imports. Finally, building on evidence that Spinosad may act synergistically with certain biocontrol agents, such as the entomopathogenic fungus *Metarhizium anisopliae* (Metchnikoff, 1879) (Ericsson et al., 2007), future field trials should investigate the potential for co-application. These combinations could offer a powerful strategy for proactively managing insecticide resistance by introducing multiple modes of action while potentially allowing for lower application rates.

5 | CONCLUSIONS

This 3-year field study provides evidence that a GR formulation of Spinosad, applied in-furrow at planting, is a highly effective control method for the key potato soil pests *Agriotes* sp. and *Melolontha* sp. in Romania. The treatment resulted in a greater than 80% reduction in pest activity and a corresponding decrease in tuber damage to less than 4%, significantly outperforming the conventional synthetic pyrethroid standard. The research establishes that an application rate of 12 kg/ha represents the minimum effective dose, providing optimal control while adhering to principles of economic and environmental stewardship.

For the structurally challenged Romanian potato sector, dominated by small-scale farms, this effective and simple-to-use technology offers a practical tool to increase marketable yields, enhance farm-level profitability, and contribute to national food security. Furthermore, the findings demonstrate that transitioning to effective, biologically derived pesticides can be a successful strategy for meeting the ambitious pesticide reduction targets of the European Green Deal without compromising agronomic performance. To ensure the long-term sustainability of this valuable tool, it must be integrated into a comprehensive IPM program that includes crop rotation

and other tactics to mitigate the risk of insecticide resistance. In conclusion, GR Spinosad represents a potent and timely solution for potato soil pest management, effectively aligning the immediate needs of farmers with the pressing sustainability goals of modern European agriculture.

AUTHOR CONTRIBUTIONS

Gabriel Comanescu: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; visualization; writing—original draft; writing—review and editing. **Luke Bell:** Data curation; formal analysis; supervision; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

Gabriel Comanescu declares that he was an employee of SBM Company at the time this research was conducted. The authors declare no other conflicts of interest.

DATA AVAILABILITY STATEMENT

All data relevant to this study are presented in the accompanying tables and figures. Raw data are available from the authors on request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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